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Aeration to Remove Volatile Organic Compounds from Ground Water

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AERATION TO REMOVE VOLATILE ORGANIC COMPOUNDS FROM GROUND WATER

Interim Report to the Office of Drinking Water

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Drinking Water Research Division
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Office of Research and Development
U. S. Environmental Protection Agency
Cincinnati, OH
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This interim report presents general information on the use of aeration to remove volatile organic compounds from drinking water for public health reasons. The report illustrates the types of aerators, shows where they are being used, presents a means of estimating aeration performance, identifies the problems and secondary effects of aeration, and estimates the cost of this technology.

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AERATION TO REMOVE VOLATILE ORGANIC COMPOUNDS FROM GROUND WATER

(An Interim Report)

by

O. Thomas Love, Jr., Walter A. Feige, J. Keith Carswell,
Richard J. Miltner, Robert M. Clark and Carol Ann Fronk

INTRODUCTION

Aeration, as it is applied to water treatment, is a process involving mass transfer between the liquid phase (water) and the gas phase (air). Historically, its principal application has been in the absorption or the release of gases to improve the water's palatability or to control objectionable inorganic substances such as iron and manganese. In 1935, for example, Bayliss (1) estimated over 300 water supplies in the United States were equipped to aerate for esthetic improvements. More recently (1975), however, the discovery of industrial solvents in certain ground waters has created another application for this process; that of removing volatile organic compounds from drinking water for public health reasons. This interim report presents general information on this new application, illustrates the types of aerators* and where they are being used, presents a means of estimating aeration performance, identifies the problems and secondary effects of aeration, and estimates the cost of this technology. The U.S. Environmental Protection Agency, Drinking Water Research Division (EPA-DWRD) has several full-scale aeration projects underway. When these are completed a final report on aeration will be written.

THEORY OF AERATION

The term equilibrium means a state of balance between opposing forces or actions. When water containing volatile organic compounds is exposed to

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air that is devoid of these compounds, the air-water system tries to approach equilibrium. As explained in general terms by Haney (2), the object in aerating is to accelerate this natural phenomenon "by stirring, by breaking the water into drops or thin layers, or by blowing bubbles of air through it."

Analytical chemists have long used the phenomenon of gas-liquid phase equilibrium in a procedure called "head space" analysis (3). In this procedure, a known volume of water containing the volatile compound(s) to be quantified is placed in a bottle containing a fixed volume of air. The mixture is then agitated (aerated), allowed to approach equilibrium and the headspace air analyzed for the compound(s) of interest. By determining the concentration of the organic compound(s) in air and knowing certain molecular and constitutive properties about the compound(s), the original concentration in the water can be estimated. This is done by assuming the release of volatile compounds from water into air is described by the theory of absorbing gases into water. Haney (2) cites several sources that believe this assumption is valid for gases and current thinking (4-6 and others) is this assumption holds for dilute concentrations of volatile organic compounds.

A discussion of the absorption of gases into water and the development of an important term, Henry's Law Constant (H), is given in Appendix A. Some refer to this term as Henry's Coefficient. It is generally expressed in one of three ways: atmospheres (atm); atm-m^3/mole; or dimensionless. By expressing "H" in the latter form, concentration in air divided by concentration in water, the reciprocal, 1/H [called the partition coefficient(8)] is the theoretical optimum air-to-water ratio (volume to volume) for removing a volatile organic compound by air stripping. See Reference 7 for a discussion of this. Trichloroethylene, for example, has a Henry's Law Constant of 0.48 at 20°C (9). The partition coefficient, therefore, is

1/0.48 or 2.1. Thus, at equilibrium, 2.1 volumes of air are theoretically necessary for each volume of water to to strip out trichloroethylene. Because of the usefulness of the partition coefficient for estimating aeration requirements (this is covered in detail in a later section), the units for Henry's Law Constant can be converted as shown in Appendix A and summarized below.

To express "H" as dimensionless at 20°C (293°K) and 1 atm:

- multiply "atm" by 0.000748 (7.48×10^{-4})
- multiply "atm-m^3/mole" by 41.6

Films formed at the air-water interface influence the diffusion rate for volatile compounds and thus the time the system takes to approach equilibrium. Figure 1 is taken from an illustration presented by Haney (2) but similar illustrations are widely used to describe a simplified "two-layer"

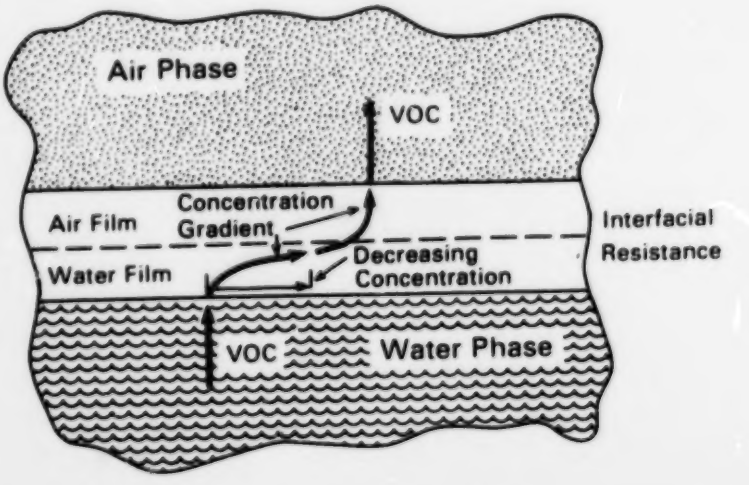

Figure 1. Transfer of a Volatile Organic Compound (VOC) from Water to Air (2).

model" of gas absorption/desorption. Taking as an example the transfer of a volatile organic compound from water to air, the compound must move out of the water, through both the water and air films, then into the air.

The rate at which the volatile organic compound is transferred across the air-water interface depends on the resistance in the films at the boundary layers. The overall transfer rate constant, commonly called "K_La", is the sum of the individual rate constants for the water and gas films. Roberts and Dandliker (6) give a good explanation of K_La and its derivation.

The total resistance, and thus the impairment to the rate of transfer from these films, can be reduced by agitation or by increasing the interfacial area for diffusion. This was clearly demonstrated by Smith (10) in a laboratory study using various concentrations of trichloroethylene, tetrachloroethylene, and 1,1,1-trichloroethane. He found the average half life (i.e., 50 percent decline in concentration) for these three compounds was approximately 110 minutes in a quiescent basin. The half life, however, decreased an order of magnitude when the water was mechanically stirred or sparged with air, or when a fan provided steady air movement over the basin.

The object of aeration, therefore, is to insure that a large amount of "clean" air is continuously being introduced to a relatively small amount of water containing the volatile organic compounds. This increases the interfacial area and maximizes the departure from equilibrium which provides the driving force for diffusion. The devices used to accomplish the transfer of volatile organic compounds from water to air are described in the next section.

TYPES OF AERATORS

In practice, aeration can be broadly characterized in two ways: putting air through water and putting water through air. In the first method, mass transfer takes place around bubbles and the practical upper limit for the air-to-water ratio is probably around 20 to 1 (volume to volume). The "water through air" method creates a thin layer or water droplets to facilitate mass transfer. Although air-to-water ratios as high as 3000 to 1 have been reported (11), air-to-water ratios are generally less than 100 to 1. Each category has several devices that will be discussed. A schematic drawing of each aerator type is shown in Figures 2 and 3.

1. Putting air through water.

   A. Diffused-air aeration (Figure 2a)

      Compressed air is injected into the water through perforated pipes or porous plates. These are sometimes called injection or bubble aerators and are more commonly used for transferring oxygen into waste water. One advantage of this type of aeration is that a system can be put into operation very quickly using existing facilities. Reservoirs, caisson wells, and even well casings and well bores have served as temporary "aeration basins." The latter scheme (Figure 2b) is currently (1984) being evaluated at a utility in Pennsylvania (12).

   B. Air Lift Pump (Figure 2c)

      This approach combines air stripping with pumping. Early in the 20th century, air-lift pumps were commonly used in the United States. These are simple devices with only two pipes in the well. One pipe introduces compressed air into the open bottom of the other pipe, called an eductor. In the

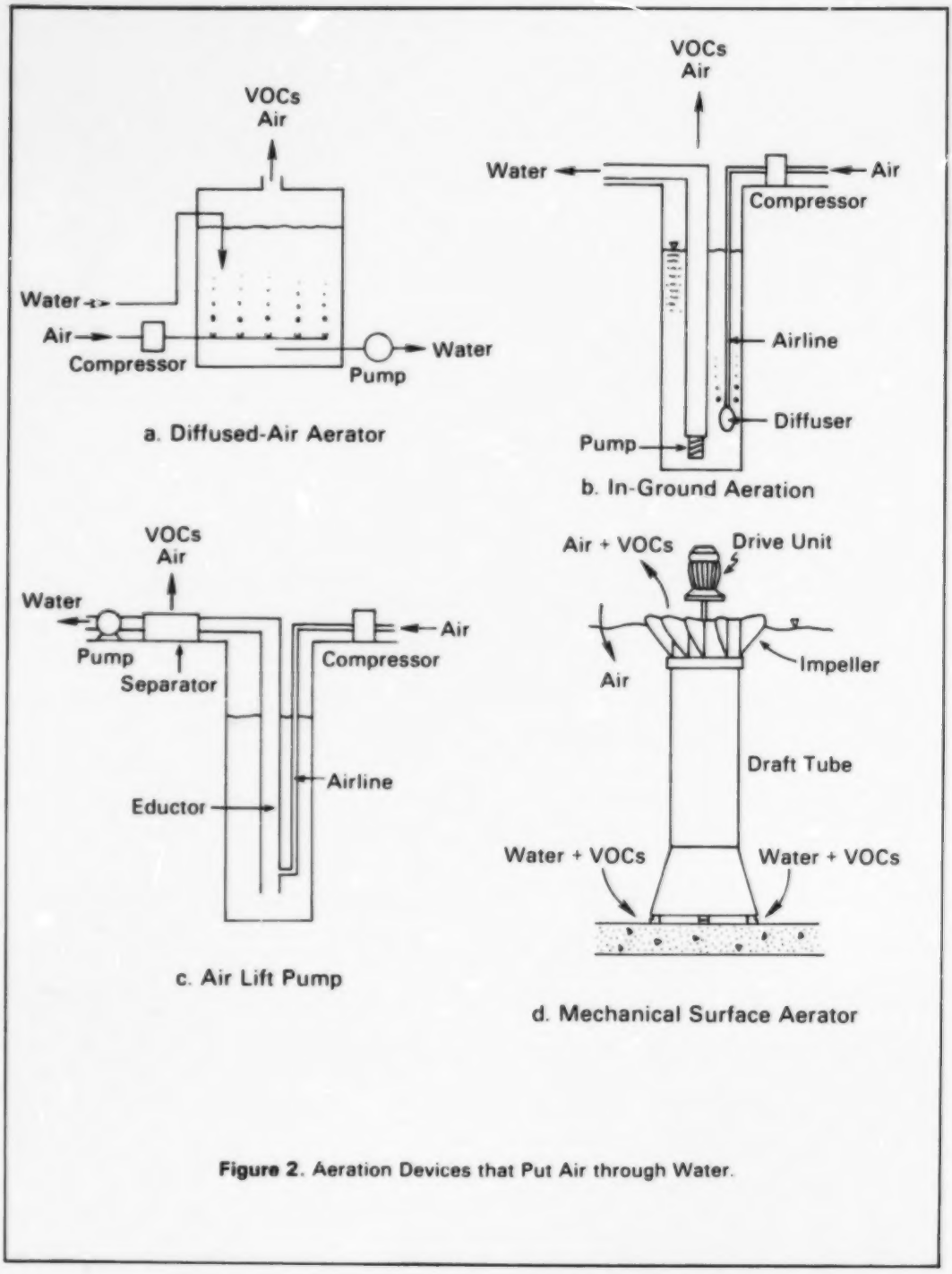

Figure 2. Aeration Devices that Put Air through Water.

eductor, air mixes with water. The mixture, being less dense than the surrounding water, will rise. Subsequently, the air and the volatile organic compounds are separated before the water is pumped into the distribution system. Because of poor pumping efficiency, typically 35 percent, air lift pumps fell into disuse with the introduction of submersible pumps. The North Penn Water Authority conducted in-depth experiments to see if resurrecting this technology could be less costly (trading poor efficiency for reduced capital costs for construction) than other treatment alternatives, but they concluded air lift pumping/aeration has very limited application (12).

C. Mechanical Surface Aeration (Figure 2d)

Like diffused-air aeration, mechanical surface aerators are commonly used in waste water treatment, but Roberts and Levy (13) see these devices as offering many advantages for air stripping of volatile organic compounds from drinking water. Several types are available. They can be mounted on platforms, bridges or supported by columns or pontoons. A motor-driven impeller-like turbine creates turbulent mixing of air and water. This device actually fits into both air-through-water and water-through-air categories.

II. Putting Water Through Air

A. Packed Tower Aerators (Figure 3a)

This device consists of a column, 1 to 3-m in diameter and 5 to 10-m in height, that is filled with "film" packing material. This "film" packing can be glass, ceramic, or plastic and is available in numerous geometrical shapes to create a water

film and thus enhance transfer of volatile organic compounds to the gas phase. The inside wall of the aeration column has several "redistributors" that force the water to flow over the packing and thus prevent the water from simply running down the walls. The diagram in Figure 3a shows a fan at the top. This is called an "induced draft" packed tower. Perhaps a more common alternative is the "forced draft" packed tower where a blower positioned at the bottom of the tower forces air up through the packing. Several excellent references (4,5,14-17) are available that describe these devices and show how they can be designed to remove 98 percent or more of the volatile organic compounds found in ground water.

B. Wood Slat and Tray Aerators (Figure 3b)

A schematic drawing of a typical slat aerator shows water is pumped into the top of the device, distributed over the cross-sectional area by a perforated plate, and allowed to trickle down and over "splash" packing, which, in this case, is redwood slats. Water splashing on the slats creates the air-water interface for mass transfer. The slats are staggered to prevent the water from short circuiting. Air is pulled into the bottom of the tower by fans mounted on top or blown into the bottom as described earlier for packed towers. The air travels upward counter-current to the water flow. These devices are commonly used for controlling inorganic compounds (iron, manganese, hydrogen sulfide, carbon dioxide) in drinking water and units have been modified (additional blower and slats) to contend with trace organic contamination (18). Tray aerators (not shown in Figure 3) and cooling towers are also

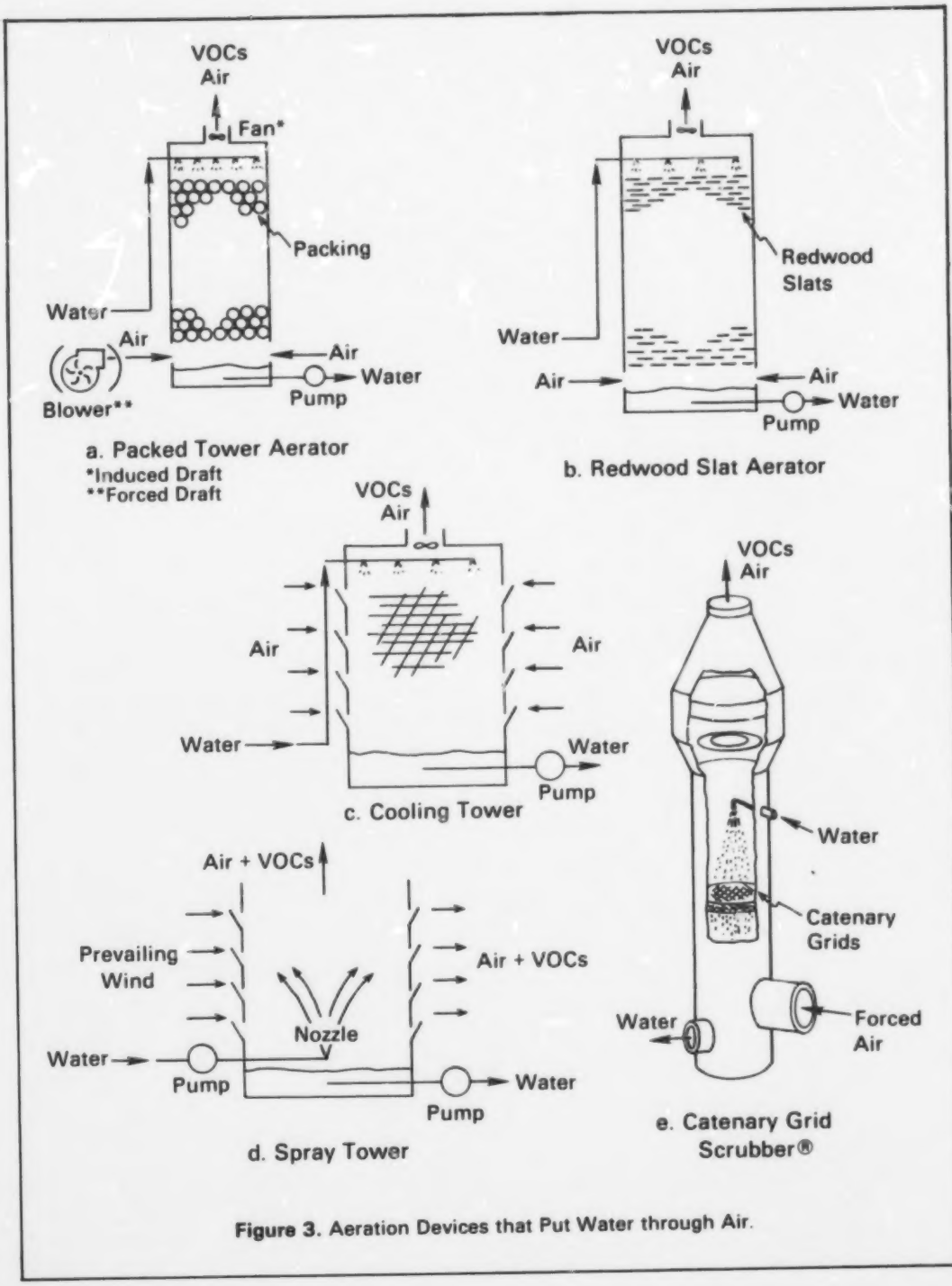

Figure 3. Aeration Devices that Put Water through Air.

included in the water-through-air category, but cooling towers (Figure 3c) differ in that the air movement might be cross-current, rather than countercurrent as it is in wood slat and packed tower aerators.

C. Spray Aerators (Figure 3d)

According to the Cheremisinoffs (19), these devices evolved from spray ponds that were surrounded by louvered walls. By spraying water through nozzles, small droplets having a large interfacial surface area are produced. In a natural draft spray tower, air movement is dependent on the atmospheric conditions and the aspirating effect of the nozzles. Spray towers are generally placed side by side at right angles to the prevailing winds.

D. Catenary Grid Scrubber®* (Figure 3e)

This is a proprietary device that was developed as an air scrubber (20), but might have an application in removing volatile organic compound from water. A fluidized gas-liquid contact is created by balancing the air flow velocity profile through catenary-shaped grids. These grids, generally placed in pairs, are stainless steel wire mesh with 0.6 to 2.5 cm openings. The manufacturer reports a very low air pressure drop and speculates that this device would be perhaps one-half the height of a packed tower. This device, however, has not been tried on a full-scale using a solvent-contaminated ground water so its future in this application remains unknown.

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* Chem-Pro Corporation, 17 Daniel Road, P.O. Box 1248, Fairfield, NJ

LOCATIONS OF AERATION FACILITIES

Figure 4 represents those sites that incorporate or plan to incorporate aeration as a treatment technique to remove volatile organic contaminants from ground water sources of drinking water. In some cases, systems are now in operation. In others the design and construction phases are taking place, and in still others, pilot plant research is being conducted. Table 1, a compilation of information from the EPA regional offices, identifies specific locations across the United States. Where the information is available, a description of the installation appears, in addition to the major contaminants treated and the concentrations detected. A consistent format is lacking because of the variety of ways the input was given to us. To date, approximately 2/3 of the three dozen or so aerators installed are packed towers.

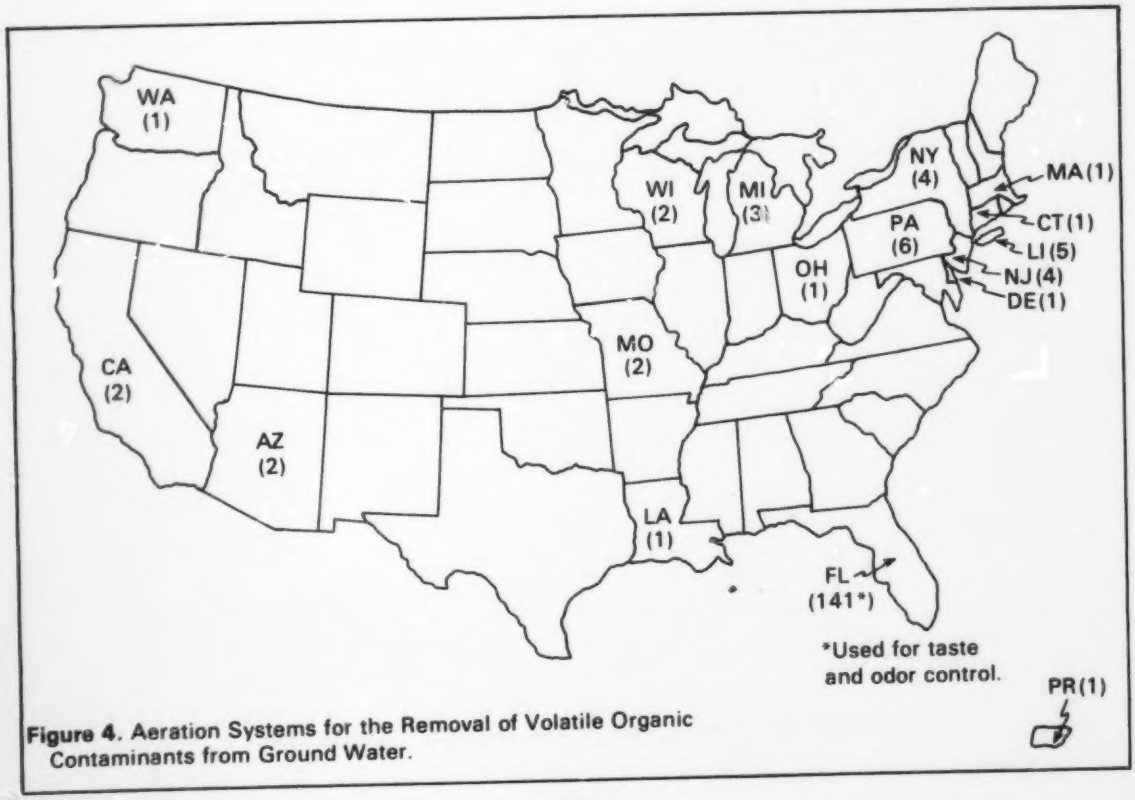

Figure 4. Aeration Systems for the Removal of Volatile Organic Contaminants from Ground Water.

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TABLE 1
AERATION SYSTEMS FOR THE REMOVAL OF VOLATILE ORGANIC CONTAMINANTS FROM GROUNDWATER

Location	Type	Brief Description	Major Contaminants* (Inf. Conc. Range-ug/L)	Relevant Information
ALABAMA, ALASKA	None Reported			
ARIZONA				
Scottsdale	Packed Tower	Forced Draft (Blower)	TCE (40-250)	System may be on-line during summer of 1984. 12' diam x 30' high with 18' of 2" Jaeger Tri-Pac packing. Design flow 2,500 gpm, air flow 7,500 cfm to be supplied by a 20 hp blower. Design A/W = 20/1 to produce TCE levels < 5 ug/L, the AZ action level. Notes: 1) column to be of aluminum construction and sunk 20' into ground to adhere to zoning laws 2) Intake filter on the blower should remove particulate matter from the air 3) monitoring of the discharged air to be performed.
Tucson	Packed Tower	Forced Draft (Blower)	TCE (200)	Conceptual and treatment design has been completed for the Air Force. Construction > 1 yr. away. Water to be treated: 2,500 - 5,000 gpm.
ARKANSAS	None Reported			
CALIFORNIA				
LaCrescenta	Packed Tower	—	TCE (15-20)	Primarily designed for CO_2 removal, but removes 30-40% TCE. Tower is 3' diam x 10' high and contains plastic packing.
Baldwin Park	Packed Tower	—	TCE (6-1,800) TETRA (18-65) 1,1,1-TRI (15- >20) $CHCl_3$ (10-60)	Pilot and full-scale studies to be conducted during this research project. Full-scale tower estimated to be operating in 1984. Unique feature is elevated storage to minimize pumping. Secondary effects of aeration to be examined including particulates, air emissions, and microbiology.
COLORADO	None Reported			
CONNECTICUT				
Norwalk	Redwood Slat-Tray	one unhoused aerator, induced draft via top-mounted fan	TCE (7-142) CIS (<0.1-12)	Installed May 1981, aluminum construction 10 ft x 12 ft x 16 ft (high), 1,000 gpm treated water; 65% VOC removal at A/W = 28/1; inorganic and microbiological parameters monitored during research project.
DELAWARE				
Smyrna	Redwood Slat - Tray	two induced draft aerators	TCE (20-70)	One aerator was installed in 1978, the other is a converted CO_2 removal unit. Each is 8'4" square by 13' high, operates between 825 and 1,000 gpm; air is supplied by 2-2 hp blowers @ 6,000 cfm each; 50% TCE removal, effluent further treated by granular activated carbon. Installed cost for each aerator $25 K (1983 dollars).

*Legend

TCE = trichloroethylene
TETRA = tetrachloroethylene
1,1,1-TRI = 1,1,1-trichloroethane (methyl chloroform)
$CHCl_3$ = chloroform
CIS = Cis-1,2-dichloroethylene

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TABLE 1 (Cont'd)

Location	Type	Brief Description	Major Contaminants* (Inf. Conc. Range-ug/L)	Relevant Information
FLORIDA	—	—	—	141 community public water systems that serve over 1000 people use aeration mostly to control taste and odor problems from iron and hydrogen sulfide. A complete listing is available.
GEORGIA, HAWAII, IDAHO, ILLINOIS, IOWA, KANSAS, KENTUCKY	None Reported			
LOUISIANA				
Bastrop	Cascade		Benzene (0.7-80) Toluene (< 0.5 - 12)	Aerator originally designed for H_2S and CO_2 removals.
MAINE, MARYLAND	None Reported			
MASSACHUSETTS				
Wilmington	Redwood Slat-Tray	two housed aerators, parallel operation, induced draft via 2 top-mounted fans	TCE (8-284) CIS (2-20) TETRA (<0.1-3)	Installed June 1981, aluminum construction, 10 ft x 10 ft x 15 ft (high), 0.5-1.5 mgd water treated; >90% VOC removal at A/W from 50/1 to 100/1; Inorganic and microbiological parameters monitored during research project; iron fouling of distributor plates took place.
MICHIGAN				
Charlevoix	Diffused Air in a dug well	—	TCE (30)	TCE removal = 30%
Clare	Induced Draft		TCE (?)	Incorporates pressure filtration for iron removal. A blower was added to increase A/W. Result 60% TCE removals.
Wurtsmith AFB	Packed Tower	Forced Draft (Blower)	TCE (50-8,000)	System went into operation May 1982 and was stopped in late 1983 because of stringent effluent requirements imposed by the State. Two columns, each 5' x 35' high, contain 18' of 5/8" Pall Ring packing. Columns are unhoused, but pumps are housed. Flow 1,200 gpm in parallel or 600 gpm in series. Each tower removed 98% TCE and 99.9% in series at A/W = 25/1. Design and construction costs = $185K.
MINNESOTA, MISSISSIPPI	None Reported			
MISSOURI				
Liberty	Packed Tower	Forced Draft (Blowers)	TCE (36-69) 1,1,-D1 (11-22)	Original aeration system that was used for iron and manganese removal was upgraded for VOC removal in the fall of 1983. Plastic pall rings become plugged, and three levels of aluminum grates were installed to facilitate cleaning. VOC removals increased from 30% to 80%.
Valley Park	PVC Slat Trays	Forced Draft (Blowers)	TCE (180-370) 1,1,1-TRI (120-190)	Dimensions 7' x 10' x 10' high, molded fiberglass reinforced polyester. Two blowers, each 3,300 cfm at design capacity of 2 mgd. Aeration effluent split into two concrete detention basins. Aeration efficiency 70-80%.

TCE = trichloroethylene
TETRA = tetrachloroethylene
1,1,-D1 = 1,1-dichloroethylene
1,1,1-TRI = 1,1,1-trichloroethane (methyl chloroform)
? = information unknown

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TABLE 1 (Cont'd)

Location	Type	Brief Description	Major Contaminants* (Inf. Conc. Range-ug/L)	Relevant Information
MONTANA, NEBRASKA NEVADA, NEW HAMPSHIRE	None Reported			
NEW JERSEY				
Camden	Redwood Slat-Tray	Induced Draft (2 blowers)	TCE (20-35) TETRA (8-20) 1,2-DCE (<10-20) CCl_4 (<5)	Aerator originally used for CO_2 removal. Three wells treated by one aerator, 12' high x 180 ft^2 cross-sectional area. Blowers operate at 5,100 cfm each, resulting in A/W = 30/1. VOC efficiency 50-60%. Problems with contaminated exhaust air recirculated into air intakes. VOC efficiency increased to 65-75% when recirculation was prevented.
Fairfield	Packed Tower	Forced Draft (blower)	TCE (26-400) 1,1,1-TRI (17-291) TETRA (<2-172) TRANS (<1-51) 1,2-DCE (<1-48) $CHCl_3$ (2-19)	Spring 1984 construction anticipated. Designed to achieve <10 ug/L per compound and overall 96% VOC removal.
Rockaway Township	Packed Tower	Forced draft (blower)	TCE (50-220) 2 others (37-47)	Designed and built by major oil company, aluminum cylinder 9' diam x 40' high, contains 25' of 3-inch polypropylene packing; about 2 mgd of water can be treated; 27,000 cfm blower capable to supply air at A/W = 144/1
Rocky Hill	Packed Tower	two housed aerators, series operation, induced draft via 2 top-mounted fans	TCE (45-95) TETRA (1.5-3.2)	On-line since July 1983; each aerator 6' diam x 13' high, fiberglass construction, contains 10' of packing; 118-260 gpm water treated, A/W = 83/1. Fans have air flow = 2,000 cfm per tower and are powered by 1/4 hp motors; removal efficiency 92 - >99% for both contaminants.
NEW MEXICO	None Reported			
NEW YORK				
Brewster	Packed Tower	Forced draft (fans)	TETRA (420-470) TCE (30-48) CIS (60-77) VC (5-6)	Column under construction, 4'9" diam. x 17'8" high, designed to treat 0.5 mgd; 3" polypropylene packing; air supplied by 2 fans providing 1,530 cfm, A/W = 33/1.
Town of Hyde Park (Haviland Apts.)	Spray Aeration	?	?	On-line since Dec. 1983, designed for 95% ? efficiency
Village of Endicott, NY City of Olean, NY Citizens Water Supply Co., N. Hempstead, LI Garden City Park Water Dept., N. Hempstead, LI Hicksville Water Dept., Oyster Bay and Hempstead, LI	Packed Towers		?	As of this writing, all sites have proposals pending for approval to install packed towers.

*Legend

TETRA = tetrachloroethylene
TCE = trichloroethylene
1,2-DCE = 1,2-dichloroethane
CCl_4 = carbon tetrachloride
TRANS = Trans-1,2-dichloroethylene
CIS = cis-1,2-dichloroethylene
VC = vinyl chloride
$CHCl_3$ = chloroform
1,1,1-TRI = 1,1,1-trichloroethane
? = information unknown

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Table 1 (Cont'd)

Location	Type	Brief Description	Major Contaminants* (Inf. Conc. Range-ug/L)	Relevant Information
NEW YORK (Contd)				
Lake Success (Jamaica Water Supply Co.)	Packed Tower	Forced Draft (Blower)	TCE (20-40) TETRA (< 5)	Design is 95% completed, Spring 1984 anticipated to be operational. Column construction to be reinforced concrete and rectangular. Dimensions 12' x 7' x 30' high and contains 21' of Tripac packing. Design flow 2,400 gpm, air flow 14,000 cfm (A/W = 41/1). Designed for 97% TCE removal.
Glen Cove	Diffused, Packed Tower, Induced-Air, plus others.	—	TCE (117-277) TETRA (33-207) CIS (38-79)	This 4-yr pilot plant study was completed in 1983 and evaluated several aeration designs. Systems that incorporated packing materials exhibited the best removals. Air emissions from some of the systems were examined. Final report available for purchase.
NORTH CAROLINA, NORTH DAKOTA,	None Reported			
OHIO				
Zanesville	Packed Tower	Forced Draft (Blower)	TCE (15,000-20,000) TRANS (3,000)	Industrial application, whereby the aquifer is being purged of VOC's. Ohio EPA requires total VOC levels $\leq$ 580 ug/L before discharge into river. Aerator is constructed of stainless steel 4'diam x 28' high and contains 20' of Tripac packing. Design flow 300 gpm, airflow constant @ 1,850 cfm (A/W = 45/1). VOC removal design efficiency = 97%. Iron clogging problems solved by dilute acid use.
OKLAHOMA, OREGON	None Reported			
PENNSYLVANIA				
Bristol Borough, PA	Redwood Slat - Tray	Induced Draft (2 blowers)	TETRA (110) TCE (34)	Aerator is 10' x 10' x 12' high. Water treated is 800 gpm and air is supplied by 2 - 1.5 hp blowers @ 8,000 cfm each. Approximately 70% VOC removal.
Lansdale, PA	Air-lift Pump In-well Diffused Air Aeration	—	TCE (600-1300) CIS (400 - 800) TCE (80 - 200) 1,1,1-TRI (5 - 15) VC (20 - 50)	This research project was started in 1982 and should end in late 1984. The air-lift pump has produced TCE removals from 40 - 70% and vinyl chloride removals from 65 - 93%. A/W from 1/1 to 11/1 were investigated.
Upper Marion TWP, Montgomery County, PA	Packed Tower	Forced Draft (Blower)	TCE (3-20)	Tower is 21' diam x 30' high utilizing 14' of plastic and ceramic saddles (Jaeger Tri Pac, & Ballast Saddles). 12' of packing are 1" saddles and 2' of packing are 2" saddles. 2" saddles are at the bottom of the tower. The tower is designed for 20 MGD. It is currently processing 5 - 20 MGD with an average flow of 7.5 MGD.

*Legend

TETRA = tetrachloroethylene
TCE = trichloroethylene
CIS = Cis-1,2-dichloroethylene
1,1,1-TRI = trichloroethane (methyl chloroform)
VC = vinyl chloride
TRANS = trans-1,2-dichloroethylene

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TABLE 1 (Cont'd)

Location	Type	Brief Description	Major Contaminants* (Inf. Conc. Range-ug/L)	Relevant Information
PENNSYLVANIA (Cont'd)				
Upper Merion TWP, (Cont'd)				One 40 hp blower provides air at rates ranging from 5,000 - 20,000 cfm. Efficiency ranges from 92-94% TCE removal. Construction and start up costs are estimated at $800,000. O&M costs are estimated to be less than or equal to $75,000/yr. This system has only been in operation since October 19, 1983. Therefore, all costs are estimated.
Norristown (The Superior Tube Co.)	Packed Towers (3)	Forced Draft (Blower)	TCE (3,000 - 14,000)	Three systems are operated to decontaminate an aquifer and were installed between 1974 and 1980. The towers are from 17-36" in diameter, 5 - 20' high, and contain packing of 1/2" (2 systems) and 1" ceramic saddles,(1 system). Water flows are 15 - 29 gpm, air flows are 240 - 350 cfm, A/W from 72/1 to 175/1. TCE removal efficiencies > 98% and not affected by ambient air temperature changes.
Warminster Heights Development Co.	Diffused Air	Aerated Cistern (blower)	TCE (36) TETRA (14)	This system is used to treat a 400,000 gal water storage cistern. In 1980 when it was originally set up the system consisted of a fan to vent the air above the cistern and spray fittings on the discharge pipes from the wells to the cistern. The spray was found to be ineffective in reducing VOC levels. Therefore eight bubblers were added to the cistern. Each bubbler consists of a line of 1 1/2" plastic pipe with two rows of 1/8" holes every 2-3". 180,000 gpd are pumped to distribution from the cistern. One 1 1/2 hp vortex blower provides air at approximately 165 cfm. Efficiency ranges from 60 - 75% TCE/TETRA removal. Initial installation costs are estimated to be approximately $3,000. O&M costs are estimated to be $5,000/yr. This system experienced numerous operational problems due to the type of blower used. When the blower broke down in Aug. 1983 the company decided to refrain from repairing it and began looking into modifications to and/or changes in the existing system. The options under consideration are: 1) replace the 1 1/2 hp vortex blower with a 7 1/2 hp positive displacement blower and add baffles to the cistern or 2) install a packed tower aeration unit and discard the existing bubbler system altogether. The tower would most likely be 17' high by 2 1/2' in diameter. It is hoped that a decision on the changes to be made will be reached in the next few months.

*Legend

TCE = trichloroethylene
TETRA = tetrachloroethylene

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TABLE 1 (Cont'd)

Location	Type	Brief Description	Major Contaminants* (Inf. Conc. Range-ug/L)	Relevant Information
PENNSYLVANIA (Cont'd)				
Warrington TWP, Montgomery County	Packed Tower	Forced Draft (Blower)	TCE (130)	The packed tower is 3' diam x 31' high, utilizing 21' of 2 1/2" inert ceramic saddles and "paws" as packing material. A steel support plate (gas injection type) is used at the tower bottom to contain the packing material. Sampling ports are located every 2' along the tower beginning 8' from the bottom and continuing to within 6' of the top. Aluminum rosette distributors located every 6-7' along the tower prevent influent from adhering to the inner tower walls. 160,000 gpd of water are pumped at approximately 250 gpm. One 5 hp blower provides air at a 40:1 air/water ratio and a 0.14 psi pressure. Efficiency is 96-97% with approximately 0.2 lb TCE/day removed. Construction and start up costs for this project were in excess of $40,000. O&M costs are estimated to be $0.05/1,000 gals water processed.
PUERTO RICO				
Vega Alta, PR	Packed Tower	Forced Draft (Blower)	TCE (720-855) TRANS (41-50) DICHLOR (18-25)	System under construction. No details on packing. 600 gpm of water to be treated to meet NY State Guideline levels (50 ug/L per contaminant, total 100 ug/L).
RHODE ISLAND, SOUTH CAROLINA, SOUTH DAKOTA, TENNESSEE, TEXAS, UTAH, VERMONT, VIRGINIA	None Reported			
WASHINGTON				
Tacoma	Packed Tower(s)	Forced Draft (Blowers)	TCEA (17-300) TCE (54-130) TRANS (30-100) TETRA (1.6-5.4)	5 towers in operation since Aug. 1983, but shut down for the winter. Each tower is 12' diam. x 35' high (50' high with 4' diam. stack), and contains 21' of 1-inch plastic saddle packing. Total water flow 3,500 gpm split to each tower. Five (5) 60-hp blowers force 29,000 cfm through each tower. 95%+ VOC removals.
WEST VIRGINIA	None Reported			
WISCONSIN				
Delavan	Packed Tower	Forced Draft (Blower)	TCE (95-100)	May have a packed tower by September 1984. Same "turnkey" operation as Hartland, WI. Filter will probably be added after stripper for iron removal.
Hartland,	Packed Tower(s)	Forced Draft (Blower)	TCE (175)	"Turnkey" approach to be operational early February 1984. Dimensions 9' x 35' high, 28' of Tripac packing, guaranteed to remove 99%+ TCE at 1,000 gpm and inf. conc. of 175 ug/L. One 5 hp blower to be used, resulting in A/W = 50/1. Total cost $144K including tower, installation, piping and well pump modifications.
WYOMING	None Reported			

*Legend

TCE = trichloroethylene
TRANS = Trans-1,2-dichloroethylene
DICHLOR = 1,1-dichloroethylene
TCEA = 1,1,2,2-tetrachloroethane

PREDICTING AERATION PERFORMANCE

Several investigators have reported the efficiency of aerating volatile organic compounds (21-28) and some have attempted to relate molecular properties to performance (29,30). McCarty and coworkers (11) concluded Henry's Law Constant (H) is the most useful indicator of relative ease for air stripping volatile organic compounds. Thus, knowing "H", organic compounds can be ranked as is shown in Figure 5. The reciprocal of Henry's Law Constant (the partition coefficient) was used in Figure 6 to develop the solid black line or the theoretical optimum performance curve. This "optimum" behavior of the process is useful, but note in Figure 6, the actual operating data not only deviate from the theoretical, particularly at the higher air-to-water ratios, but a substantial range exists within the reported performance. For example, the air-to-water ratio required to remove 90 percent of the trichloroethylene ranges between 3 to 1 and 30 to 1.

The deviation of the actual data from the theoretical reflects, in part, the inability to achieve equilibrium and thus create the "ideal system." The actual performance of an aerator is represented by an operating line. An explanation of the theory of developing equilibrium and operating lines is given in Reference 4. The spread in the empirical data, on the other hand, could have been caused by either a difference in efficiency between aerators, or the background water quality matrix (e.g., total dissolved solids, total organic carbon, etc.), or both. The effects of water quality are being examined two ways: EPA-DWRD, using a diffused-air* aerator and under laboratory conditions, prepared various inorganic and organic qualities of background water with volatile organic compounds and conducted aeration tests. This work is on-going, but the findings for

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*Countercurrent flow, diffused air aerator, 10 cm (4 in) in diameter, 2 m (6 ft) long, with a sintered stainless steel diffuser

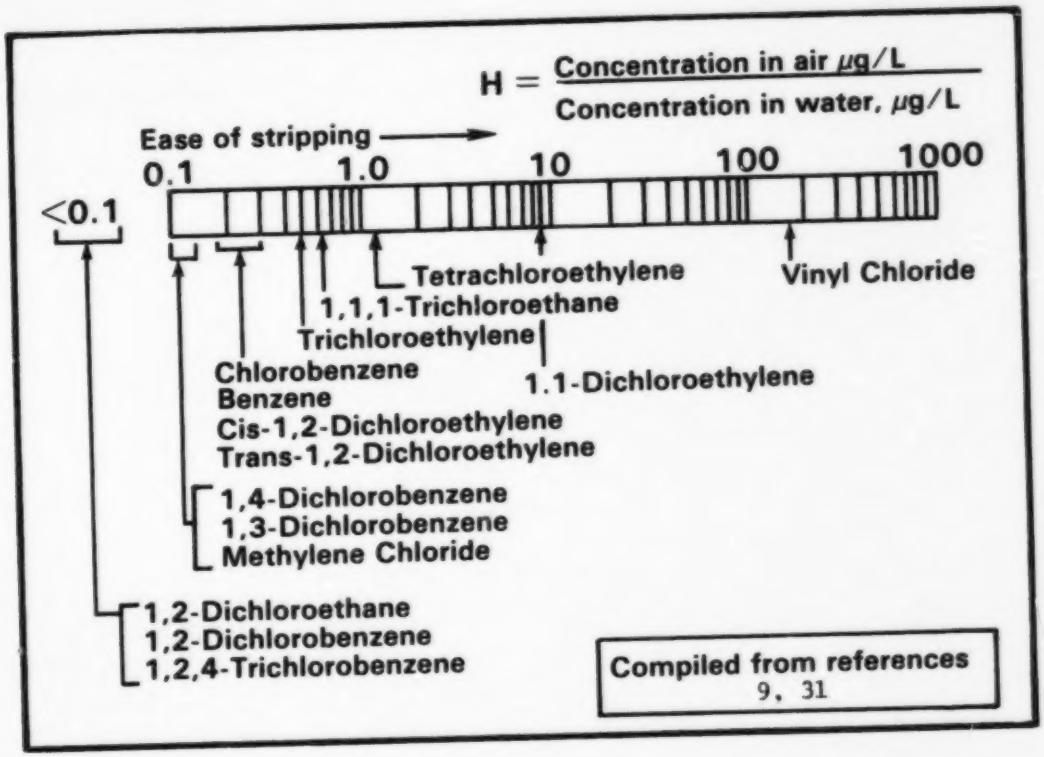

Figure 5. Comparison of Henry's Law Constants for Selected Organics.

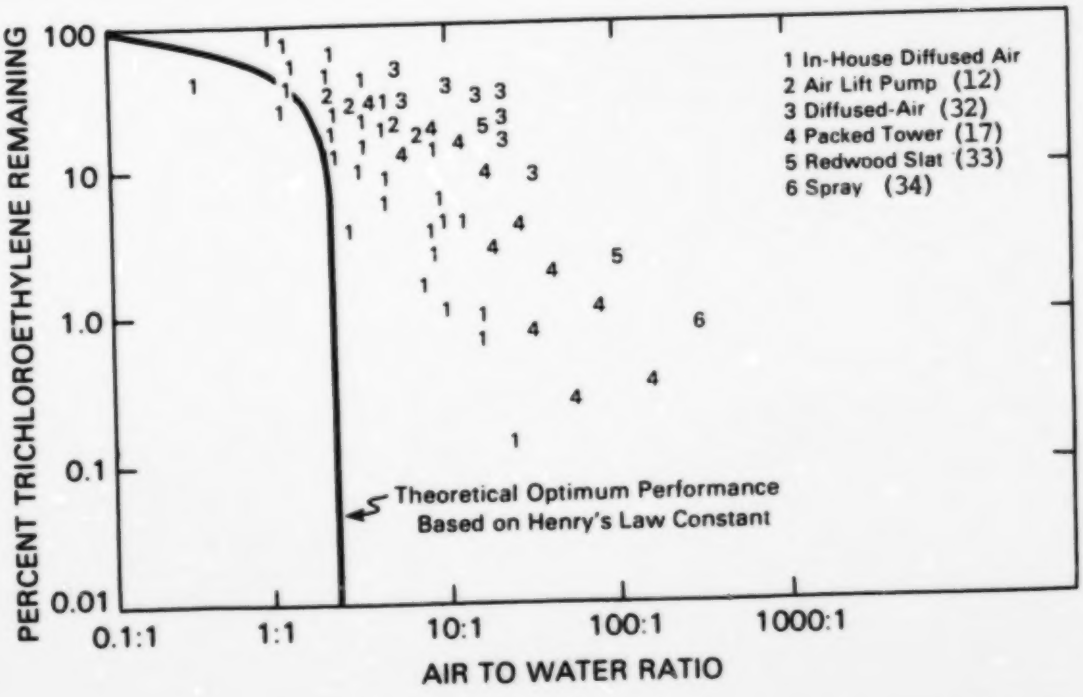

Figure 6. Comparison of Actual and Theoretical Removal of Trichloroethylene from Drinking Water by Aeration.

trichloroethylene and benzene (Table 2) suggest little effect for the modest TDS and TOC range examined.

TABLE 2. EFFECTS OF WATER QUALITY ON AERATION EFFICIENCY

TDS, mg/L	TOC, mg/L	Trichloroethylene* Percent Removal Air-to-Water Ratios 2:1	5:1	10:1	15:1
150	2.5	60	78	91	92
77	1.2	63	80	89	93
41	0.7	57	87	91	93
21	0.5	61	82	91	94
		Benzene**			
21	0.6		63	77	85
260	0.6		64	79	84

* 200 ug/L in Ohio River water diluted with distilled water
** 50 ug/L in distilled water with NaCl added

EPA's Office of Drinking Water, Technical Support Division, in a parallel effort to examine the effects of water quality (i.e., different concentrations of organics and inorganics) on aeration, constructed a pilot scale packed tower** aerator and performed field aeration tests at different sites having organic contaminated groundwater. Cummins and Westrick (15) reported little discernible effect could be attributed to water quality. The spread, therefore, in the empirical data in Figure 6 must be almost entirely related to differences in operational efficiencies between devices, rather than the background quality of the water being aerated.

**Countercurrent flow, packed tower aerator 30 cm (12 in) in diameter, 6 m (18 ft) high, forced draft, 1/2 in Telerex® packing (see References 15 and 16 for additional design details.)

One question is how can the feasibility of aeration be estimated in a more realistic fashion than simply looking at the reciprocal of the Henry's Law Constant or applying the mathematics of chemical engineering theory? One method, as suggested by Wood et al., (35) is to generate a family of air-to-water ratio curves, relating the logarithm of the Henry's Law Constant (Log H) to percent removal. Figure 7 illustrates this approach for the EPA-DWRD diffused-air study results, but this, of course, is limited to relatively low air-to-water ratios.

A simple method of estimating aeration performance [as was done by Love and Eilers (36)] is to calculate the average deviation between the theoretical and actual air-to-water ratios and use these multiplying factors. This lumps all the aeration data together and does not distinguish between types of devices. Table 3 shows some of these multiplying factors. A factor of 10 to 20 times the theoretical air-to-water ratio is probably a reasonable "estimate" for 90 percent removal by air stripping. This is not intended to replace on-site pilot-scale aeration tests. Appendix B shows a mathematical approach to predicting the necessary air-to-water ratio to achieve a desired efficiency.

TABLE 3. COMPARISON OF ACTUAL TO THEORETICAL AIR-TO-WATER RATIOS TO ACHIEVE 90% REMOVAL OF VOLATILE ORGANIC COMPOUNDS

Organic	Theoretical	Actual		Multiplying Factor*
		Range	Mean	
Trichloroethylene	2:1	2:1-30:1	16:1	8
Tetrachloroethylene	1:1	1:1-100:1	50:1	25
1,1,1-Trichloroethane	6:1	4:1-50:1	27:1	4
1,1-Dichloroethylene	0.2:1	-	2:1	10
Cis-1,2-Dichloroethylene	4:1	12:1-27:1	19:1	5

*$\frac{\text{mean actual air-to-water ratio}}{\text{theoretical air-to-water ratio}}$

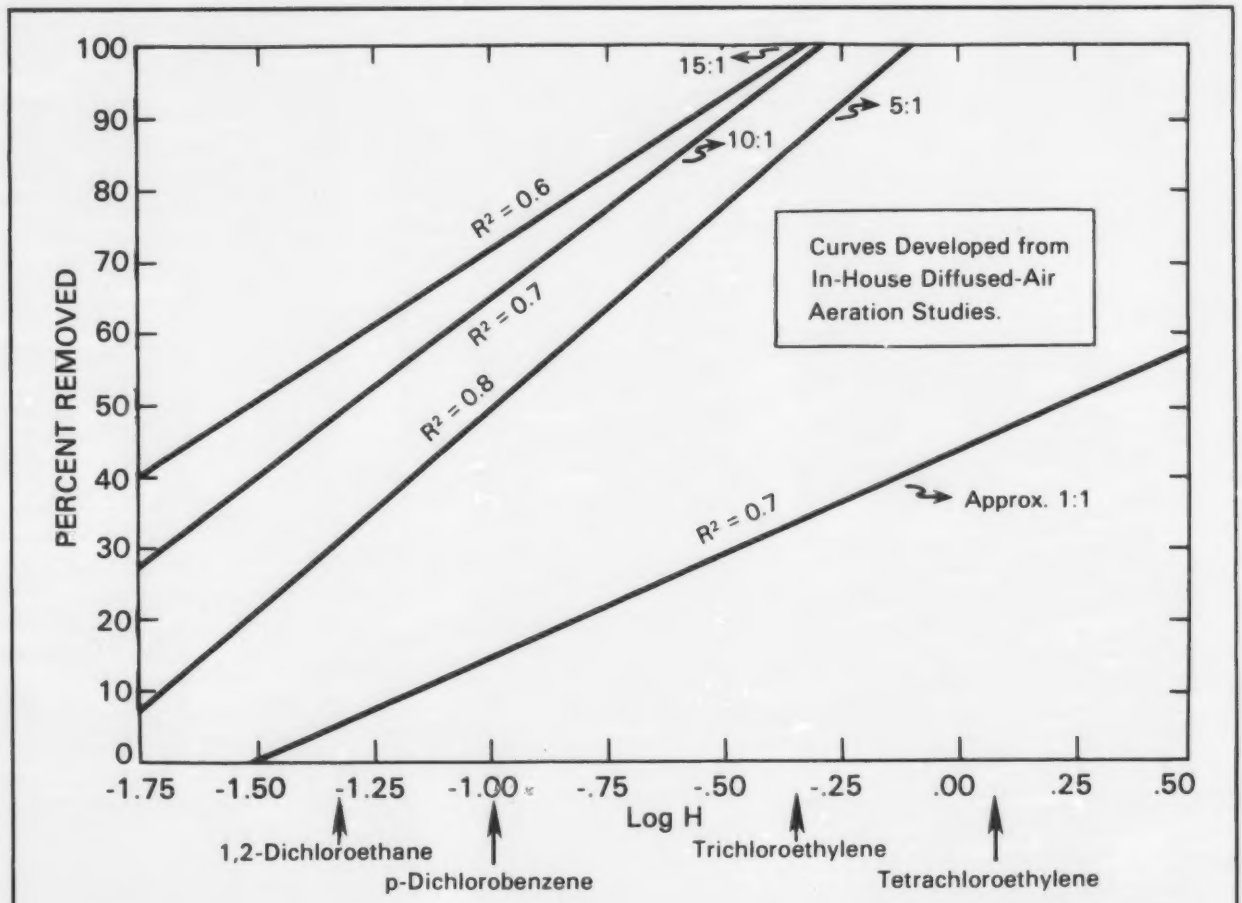

Figure 7. Use of Henry's Law Constant to Estimate Air to Water Ratio needed to Achieve a Desired Efficiency.

OPERATIONAL ASPECTS OF AERATION

Aeration has historically been used for a number of purposes other than controlling volatile organic contaminants (VOCs). It is not surprising, then, that aeration may bring about changes in water quality other than reduction in VOC concentrations. These changes, termed secondary effects, may be beneficial or detrimental to water quality. Additionally, questions have arisen on certain design and operational aspects of aeration that will be addressed in this section. Before choosing aeration as a VOC control technology, designers should consider detrimental secondary effects; in that way, one problem will not be solved at the possible expense of creating another.

What are the Potential Beneficial Secondary Effects of Aeration?

One 1958 nationwide survey of municipal water utilities found 2154 aerators in use in the United States (37). Because this was prior to 1976 and the discovery of VOCs in drinking water, these aerators were on-line for VOC control, but had been installed for a number of other water quality purposes. The most common use of aerators is to improve taste and odor. Aeration is also employed to remove methane and carbon dioxide from water.

Another common use of aeration is to control iron and manganese. The oxidation step is not instantaneous and with time the oxidized iron and manganese agglomerate to a precipitable size as oxides of the metal. Sedimentation (detention) basins and sand filters often follow aerators used for iron and manganese control to remove any precipitate before it fouls downstream processes or the distribution system. Given sufficient oxygenation and time, the precipitate may foul the aerator itself. This non-beneficial effect is covered in more detail later.

What About Exhaust Emissions and Effects on Air Quality?

Aeration is not a technology that destroys or alters VOCs, it simply transfers them to the ambient air where they are dispersed, diluted and perhaps subsequently photochemically degraded. Thus, designers must take care to ensure that state or local ambient air quality standards are not exceeded in the vicinity of the aerator. Air returned to water treatment facilities or to nearby homes or businesses, via ventilation systems, must also not exceed state or local indoor air quality standards. This is perhaps the most important secondary effect of aeration to consider so EPA-DWRD has put considerable resources into this aspect of aeration research.

The pilot-scale aeration project at Glen Cove, New York (32) incorporated some off-gas measurements. Air emissions from four aerators were monitored two to four times for VOC concentrations. When compared to OSHA 8-hour Work Room Standards (38), the effluent concentrations were found to be quite low (Table 4). None of the aerators had any measurable impact on the air in the immediate vicinity of the units.

TABLE 4. MEAN AMBIENT AIR QUALITY FOLLOWING AERATION [GLEN COVE, NY (32)]

	Concentration, ppm*					
	Type of Aerator					
Compound	Packed Tower	Diffused Air	Spray	Air Lift	Ambient Air	OSHA**
Trichloroethylene	7.35	6.16	ND	ND	ND	100
cis-1,2-Dichloroethylene	11.6	3.87	ND	ND	ND	200
Tetrachloroethylene	0.7	0.25	ND	ND	ND	100
1,1,1-Trichloroethane	ND	1.23	ND	ND	ND	350

*Parts per million, volume-to-volume, directly in the off-gas flow stream
VOC concentrations in the well water appear in Ref.(32).
** Work Room Standards (38), time weighted mean, 8-hour period
ND - Not detected at 0.5 ppm

The transfer of VOCs to ambient air is a concern of the state of Michigan. According to state statute*, the "best available technology" must be applied to treatment trains discharging to the air. Further, "carcinogens" must not be transferred to ambient air. Thus, the State requires granular activated carbon treatment of the off-gas stream from aerators used to remove VOCs from drinking water or from aerators used to remove VOCs from aquifers.

An EPA-DWRD project is underway in the Los Angeles basin of Southern California to identify the off-gas dispersion pattern, and quantify, if possible, the VOC concentrations emitted from a packed tower aerator (39). The State of California has rigid constraints on air emissions from point sources and a discharge permit was required before this aeration research project could proceed from pilot-scale operation to full-scale design. Umphres, et al., (40) documented the effort that was required to receive the air discharge permit and they discuss the State's new (January 1983) requirements for "Best Available Technology" for air pollution control.

What are the Potential Detrimental Secondary Effects on Water Quality?

Aerators are, in effect, large air scrubbers and the drinking water is in contact with 100,000 m^3 or more of air each day of operation. If an aerator is added to a treatment scheme that employs no particulate control, an increase in particulate matter in the treated water may be possible if the ambient air quality is marginal.

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*Khan, A., Air Quality Division, Michigan Department of Natural Resources, Ann Arbor, MI, Private Communication (March 1984).

Although the possibility may be remote, some researchers have cautioned that aeration may introduce bacteria to a finished water. A more plausible detrimental bacterial effect would be an increase in bacterial densities across an aerator as a result of the increased dissolved oxygen concentrations as well as an increase in nutrients from deposition on packing or from the packing itself. This is discussed under operational problems.

At Norwalk, Connecticut and Wilmington, Massachusetts redwood slat aerators were evaluated by EPA-DWRD (33) over a two-year period. The effects on the inorganic quality of the water shown in Table 5. In summary, chloride, sulfate, sodium, hardness, alkalinity, total dissolved solids, specific conductance and manganese concentrations did not significantly change across either aerator. Arsenic, fluoride, zinc, chromium, silver, lead, cadmium and mercury levels were also monitored but rarely detected. Particulates were monitored in the form of turbidity; no significant increases were noted across either aerator. Changes in bacterial quality are addressed later in this section.

A project at Glen Cove, New York (32) to evaluate several types of aerators also provided an opportunity to assess particulates in aerated waters and VOCs transferred to ambient air. Influent and effluent waters from a packed column aerator, a diffused aerator, a spray aerator and an air-lift pump were analyzed once for suspended solids and particle count. The results (Table 6) suggest no detrimental effect on water quality. Researchers at Glen Cove report the ambient air as "relatively clean" and caution that "different results may be found in areas where ambient air would contain high quantities of particulate matter." Recall that turbidity levels did not significantly change with aeration at Wilmington and Norwalk. The ambient air at both these locations, however, can be described as relatively clean.

TABLE 5. AVERAGE INORGANIC WATER QUALITY BEFORE AND AFTER REDWOOD SLAT AERATION (33)

Parameter*	Norwalk, CT		Wilmington, MA	
	Aeration		Aeration	
	Before	After	Before	After
Turbidity, ntu	0.2	0.2	1.8	1.6
Color, units	2.6	3.6	16.6	12.8
Total Dissolved Solids	144	145	190	185
Chloride	26	25	50	50
Sulfate	22	22	33	33
Sodium	15	15	28	28
Arsenic°	0.005	0.005	0.005	0.005
Fluoride°	0.1	0.1	0.1	0.1
Hardness, as $CaCO_3$	81	81	70	71
Alkalinity, as $CaCO_3$	53	56	23	24
Specific Conductance, umhos/cm	251	254	314	313
pH, units	7.4	7.6	6.6	7.2
Chromium°	0.005	0.005	0.005	0.005
Silver°	0.03	0.03	0.03	0.03
Copper°	0.02	0.02	0.08	0.02
Manganese°	0.03	0.03	0.36	0.34
Lead°	0.005	0.005	0.005	0.005
Iron°	0.1	0.1	1.3	1.0
Cadmium°	0.002	0.002	0.002	0.002
Zinc	0.03	0.03	0.02	0.02
Mercury°	0.0005	0.0005	0.0005	0.0005

*All concentrations in mg/L except as noted.
°Denotes concentration below minimum detectable.

TABLE 6. PARTICULATE WATER QUALITY BEFORE AND AFTER AERATION [GLEN COVE, NY (33)]

Parameter	Before	After
Particle Count*		
Packed Column	623	438
Diffused	100	195
Spray	100	92
Airlift Pump	74,100	2,250
Suspended Solids		
Packed Column	ND	ND
Diffused	ND	ND
Spray	ND	ND
Air Lift Pump	ND	ND

*particles/10 mL
ND - not detected @ 0.1 mg/L

What About Corrosion Problems?

As mentioned, aeration can decrease some forms of metal corrosion and can remove hydrogen sulfide and carbon dioxide that may be corrosive in some waters. Metal corrosion may also be increased by aeration, however, as a result of an increase in dissolved oxygen and the resultant change in stability. One EPA-DWRD project that includes examining water stability is described below.

In-well aeration was studied at the North Penn Water Authority in Pennsylvania (12) and pH and dissolved oxygen were monitored. Because aeration will remove some carbon dioxide, pH will generally increase. The effects on pH and dissolved oxygen were the same whether air lift

pumping was employed or whether a combination of air-lift pumping and diffused aeration in the well bore was employed. Well water pH was raised from 7.3 ± 0.12 to 7.71 ± 0.45 with aeration. pH increased with increasing air-to-water ratio, as expected. pH also increased at both Norwalk and Wilmington (Table 5).

In-well aeration saturated the well water with dissolved oxygen. Mean raw water dissolved oxygen was 1.43 mg/L. The theoretical saturation concentration at 54°F and 760 mm Hg is 10.68 mg/L; the mean aerated dissolved oxygen concentration was found to be 10.62 mg/L. The theoretical saturation concentration at 54°F under the range of pressure heads encountered in the air-lift foot piece or the in-well diffuser (108 to 258 ft of water) exceeds 10.62 mg/L. Thus, air-to-water ratio and contact time had no effect on aerated dissolved oxygen concentrations. In each case, the oxygen concentration exceeded 10.68 mg/L while in the well, i.e., the aerator, and degassed to surface saturation in the separator. For distribution systems made of iron pipe, dissolved oxygen at saturation could be detrimental.

What About Legionella and Other Bacteria Resulting from Aeration?

In both the Norwalk, CT and Wilmington, MA projects (33) the bacterial quality of the water was closely scrutinized. The data are summarized in Table 7. At both sites mean coliform levels increased, and at Wilmington mean plate counts increased. Increased densities may have been a result of increased dissolved oxygen concentrations, but were more likely a result of bacterial colonization on nutrient-rich redwood slats.

TABLE 7. BACTERIOLOGICAL QUALITY BEFORE AND AFTER REDWOOD SLAT AERATION (33)

	Heterotrophic Plate Count/mL		Total Coliforms/100 mL	
Norwalk, CT	Range	Mean*	Range	Mean**
Before	< 1 - 57,900	(222)	< 1 - 6	(2)
After	24 - 4,900	(188)	< 1 - 342	(17)
Wilmington, MA				
a. Before	1 - 103	(8)	< 1 - 2	(< 1)
After	< 1 - 18,100	(40)	< 1 - 10	(2)
b. Before	< 1 - 5,100	(50)	< 1 - 2	(< 1)
After	< 1 - 15,400	(188)	< 1 - 37	(5)

* geometric
**arithmetic
a - Up to 750 days of service
b - Between 750 and 850 days of service during iron fouling

In unrelated studies (41), bacterial densities were observed to increase during water storage in redwood tanks where dissolved oxygen concentrations presumably changed little. Isolation of Klebsiella in the aerated waters (42) is consistent with studies reporting the association of these species with redwood tanks (41) and suggests that colonization may have taken place on the wood. Eschericia, Aeromonas, and Citrobacter were isolated in aerated waters less frequently (42). Increased bacterial densities at Wilmington were more pronounced where, after two years of operation, iron deposition in the aerator caused short circuiting. The association between these two events is not understood, but may indicate the biological activity was associated with the sludge. At both locations, post-aeration chlorination ensured adequate finished water quality.

The similarity between aerators and cooling towers (the latter has been associated with Legionnaire's disease) prompted the monitoring of Legionella at Norwalk and Wilmington. These pathogens, however, were not isolated in aerated waters, or in scrapings of redwood biomass.(33)

In Northern climates, do aerators have to be protected from freezing and does the efficiency of aeration decline during the wintertime?

Cummins* made the following statement concerning a packed tower aerator at Brewster, New York.

"The pilot system at Brewster has been in continuous operation since August 1981. This time period included the Winter of 1981-1982, when the outside air temperature dipped to a low of -15°F (-26°C). The pilot system did not incur any freezing problems other than sample ports."

Fronk-Leist and Love (33), reporting on a study of redwood slat aerators in New England said:

"In summary, despite variations in the influent concentrations of volatile organic compounds, and fluctuations in air temperatures during cold and hot weather, the efficiency of aeration was not significantly affected at either site. The temperature of the ground water averaged 11°C and the water temperature before and after aeration varied less than 1°C year-round at both the housed and unhoused installations."

In discussing the aeration experiments at Soestduinen (Netherlands), Kruithof and coworkers (43) said "A disadvantage of spray aeration is the icing of the nozzles at low temperature."

Termaath (14) commented that housing may not be necessary to prevent a packed tower from freezing during wintertime operation, but some weather protection is prudent in case of pump failure and for personnel protection during routine maintenance.

What are Other Operational Problems or Practical Design Considerations?

Cummins' packed tower study* at Brewster, NY:

"During continuous operation a slime accumulated on the packing material. It was uncertain if the slime was biological or chemical in nature. This slime buildup undoubtedly decreased the stripping performance, increased the air pressure drop, and could pose a possible biological problem. Possible methods of cleaning the column include flushing with a large volume of water, acid cleaning, and pretreatment to remove iron. It should be noted that the mass transfer coefficient design equations were based on data collected before the slime buildup occurred. Thus, if the slime is not (or cannot) be controlled, then the removal efficiency and blower economics will degrade over time."

---

*Michael D. Cummins, Office of Drinking Water, Technical Support Division, Cincinnati, OH. Private communication, March 1982.

Fronk-Leist and Love (33):

"After approximately two years of operation, the efficiency of aeration at Wilmington began declining and deterioration in the bacteriological quality of the aerated water became evident. These redwood slat aerators were built without inspection ports, so routine examination of the internal appearance of these devices is very difficult as it requires removing a part of the aluminum shell. This is definitely a shortcoming in the design of these units. When the Wilmington Water Works personnel removed the sides from the aerators, they found iron sludge had accumulated 15 to 20 centimeters thick (6 to 8 in.) on the top distributor plate. This sludge was blocking the exit holes and the water was being short circuited down the sides of the aerator. In retrospect, a review of the inorganic data showed approximately 0.2 mg/L of iron was being removed through aeration. Over the course of a year of continuous running, between 400 to 500 kg of iron would be expected to accumulate in each unit. At Wilmington, the operators used fire hoses to wash down the iron sludge and now have an annual maintenance program for cleaning the interiors of their aerators."

This experience points out two important considerations when contemplating aeration. The first is the iron concentration in the raw water. If this concentration exceeds 0.5 mg/L, the designer probably should consider some iron control process to avoid maintenance problems. Secondly, all aerators should have easy access to their interior to allow routine inspection and cleaning.

In discussing diffused-air aeration at Peace River, FL, Singley and Williamson said (44);

"Operating at a greater water depth results in improved performance for all air-to-water ratios tested. This result has a significant impact on the design approach for diffused aeration. As air-to-water ratios increase, the size and costs of operating large compressors necessary for supplying air become significant and may negate any performance improvement of operating at the higher air-to-water ratio. Therefore, it becomes important to obtain the most efficient performance possible at lower air-to-water ratios. These studies indicate that more efficient performance occurs as the aeration depth increases."

Although this may be the case with diffused-air aeration basins, it is not necessarily the case with in-well diffused-air aeration. With the latter, efficient performance also depends on the location of the diffuser relative to the zones of contaminated strata (12).

COST OF AERATION

In this section aeration costs are developed on the basis of estimated performance data and compared with actual costs of installing and operating an air stripper. Table 8, taken from Love and Eilers (36), summarizes estimated air-to-water ratios for stripping volatile organic chemicals from water. In Table 8 an influent concentration in ug/L is given versus the effluent concentration to be achieved. For example, if we wish to reduce an influent concentration of trichloroethylene from 1000 ug/L to 0.1 ug/L, the estimated air-to-water ratio is 76:1. These air-to-water ratios are used for both diffused air and packed tower aerators, but recall, the practical upper limit for diffused air aeration is approximately 20:1.

The treatment costs estimates are based on the configuration shown in Figure 8. In this case, a ground water source is assumed together with one of two technologies: packed tower or diffused-air aeration. The effluent stream from the treatment process is chlorinated, goes to a clear well, and then is distributed through highlift pumps. In this example, we will examine the cost tradeoffs between the two technologies assuming flows of 0.5 MGD (1,900 m^3/day), 1 MGD (3,800 m^3/day), and 10 MGD (38,000 m^3/day) all operating at 70 percent capacity.

The following assumptions are used for the packed towers. The towers are assumed to be rectangular, with a height of 10 ft (3 m), with an air supply of 52 standard cu ft/min/sq ft (264 standard liters/min/sq m) of surface area. They are assumed to have electrically-driven induced draft fans, stack and drift eliminators. The tower costs do not include supply pumps or underflow pumps.

TABLE 8. ESTIMATED AIR-TO-WATER RATIOS NECESSARY TO ACHIEVE DESIRED WATER QUALITY (36)

	Inf. conc., ug/L	Effluent concentration, ug/L				
		0.1	1	10	50	100
Trichloroethylene	1000	76:1	54:1	32:1	17:1	11:1
	100	54:1	32:1	11:1	1:1	-
	10	32:1	11:1	-	-	-
	1	11:1	-	-	-	-
Tetrachloroethylene	1000	96:1	72:1	45:1	26:1	18:1
	100	72:1	45:1	18:1	1:1	-
	10	45:1	18:1	-	-	-
	1	18:1	-	-	-	-
1,1,1-Trichloroethane	1000	198:1	90:1	35:1	14:1	8:1
	100	90:1	35:1	8:1	1:1	-
	10	35:1	8:1	-	-	-
	0	8:1	-	-	-	-
Carbon tetrachloride	1000	19:1	15:1	10:1	6:1	4:1
	100	15:1	10:1	6:1	1:1	-
	10	10:1	6:1	-	-	-
	1	6:1	-	-	-	-
Cis-1,2-Dichloroethylene	1000	104:1	77:1	52:1	34:1	26:1
	100	77:1	52:1	26:1	4:1	-
	10	52:1	26:1	-	-	-
	1	26:1	-	-	-	-
1,2-Dichloroethane	1000	56:1	42:1	28:1	18:1	14:1
	100	42:1	28:1	14:1	-	-
	10	28:1	14:1	-	-	-
	1	14:1	-	-	-	-
1,1-Dichloroethylene	1000	10:1	8:1	5:1	3:1	3:1
	100	8:1	5:1	-	-	-
	10	5:1	3:1	-	-	-
	1	3:1	-	-	-	-

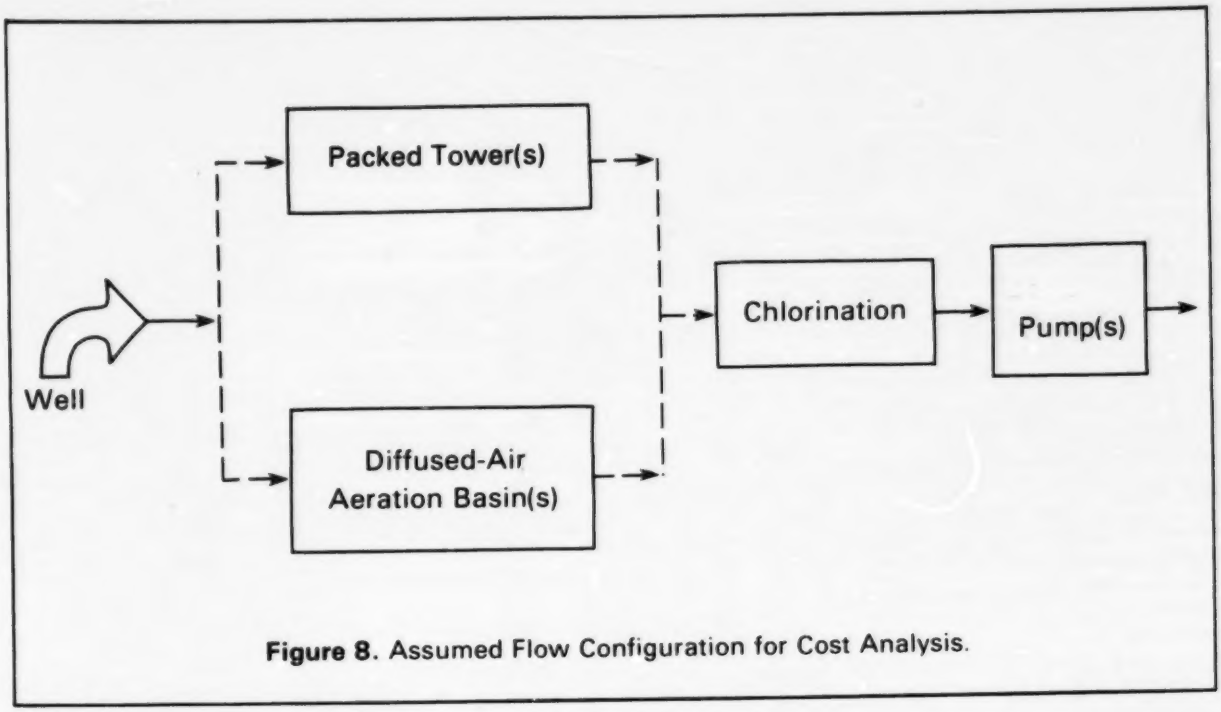

Figure 8. Assumed Flow Configuration for Cost Analysis.

Figure 8. Assumed Flow Configuration for Cost Analysis

Aeration basins are also assumed to be rectangular, with a depth of 12 ft (3.5 m) with a diffused air supply of 5 standard cu ft/min/sq ft (14 standard liters/min/sq meter) of basin floor area. Standardized cost curves (45) are used for estimating costs for the technology used.

The assumptions for chlorination include a feed system and a building for cylinder storage. The assumed dose is 2 mg/L and the cost of chlorine is $320/ton (35¢/kg). Clearwell storage was assumed to be above ground with a capacity equal to 10 percent of the daily flow. The pump was assumed to have a head of 40 ft (12 m). Not included were expenditures for land, aerator housing, corrosion control, fences, or off-gas handling. Table 9 contains specific assumptions for this cost analysis example.

Cost and Performance Calculation

Using the cost data, the design assumptions and the estimated performance, cost comparisons were made between the two aeration schemes to remove

TABLE 9. DESIGN ASSUMPTIONS FOR PLANT CONFIGURATIONS

		Design Flow		
		0.5 MGD ($1,900 m^3$/day)	1.0 MGD ($3,800 m^3$/day)	10.0 MGD ($38,000 m^3$/day)
Clearwell Storage - Ground Level,	gal	50,000	100,000	1,000,000
	(m^3)	(190)	(380)	(3,800)
Chlorination Feed and Storage,	lb/day	60	120	1,200
	(kg/day)	(30)	(60)	(600)
High-Lift Pumping Head,	ft	40	40	40
	(m)	(12)	(12)	(12)
Cost of Labor		$9.00/hour		
Cost of Electricity		$.05/kilowatt-hour		
Amortization Interest Rate		10%		
Amortization Period		20 years		
ENR Construction Cost Index (1984)		361		

trichloroethylene, tetrachloroethylene, 1,1,1-trichloroethane, carbon tetrachloride, cis-1,2-dichloroethylene, 1,2-dichloroethane and 1,1-dichloroethylene.

Figure 9 shows the costs for removing trichloroethylene at three design flows (46). Calculations are made for removal efficiencies between 90 and 99.99%. As might be expected the unit costs for both aerators drop with increasing design capacity. At all design levels, packed tower aeration is the cheaper technology. The unit removal costs for the volatile organic compounds considered are summarized in Appendix C. These costs include O&M costs and amortized capital costs. Taking, for example, the 90 percent removal costs, diffused air aeration is approximately twice as expensive as a packed tower.

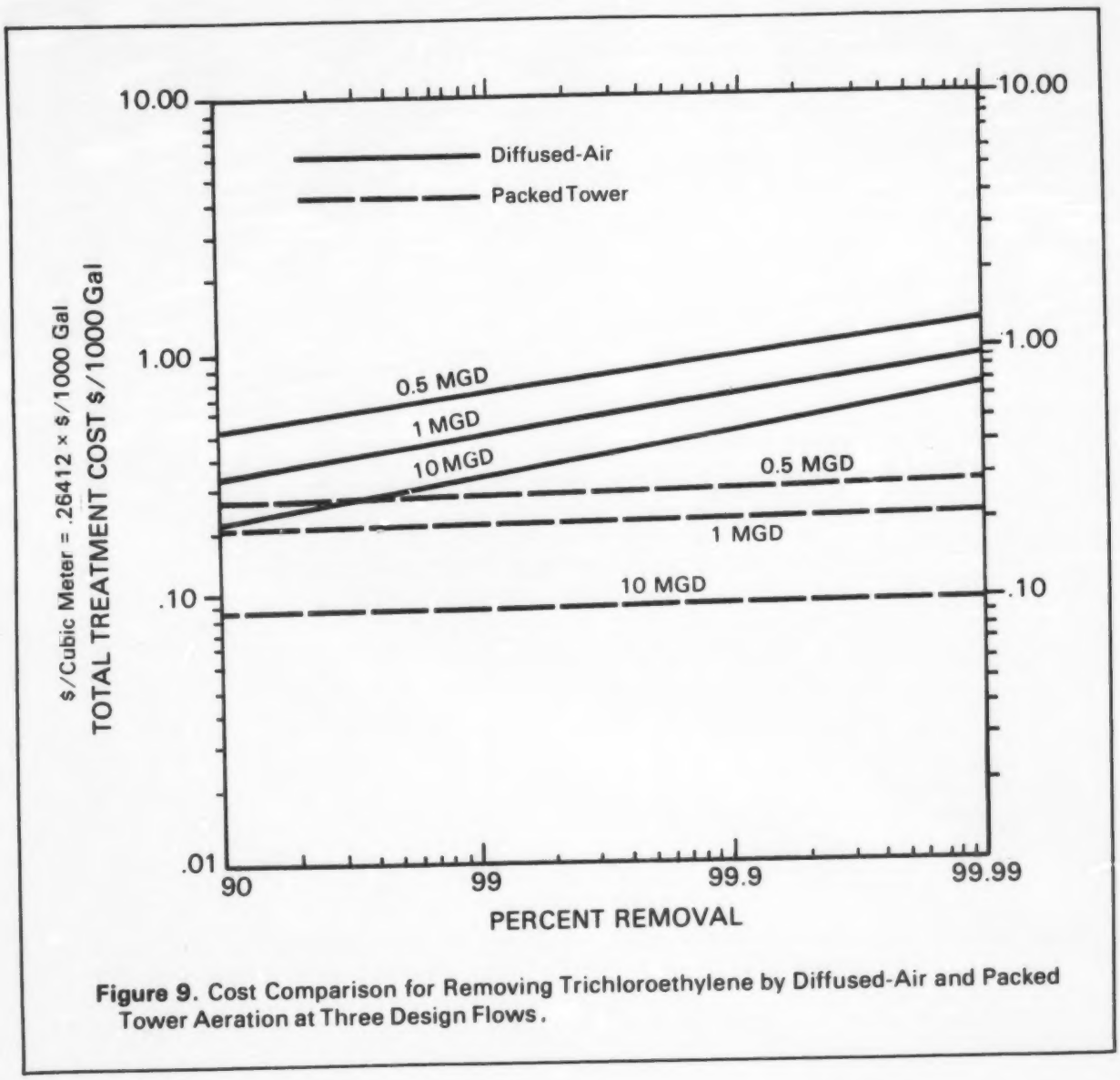

Figure 9. Cost Comparison for Removing Trichloroethylene by Diffused-Air and Packed Tower Aeration at Three Design Flows.

Two obvious factors that influence the unit costs are system size and air-to-water ratio required for desired removal efficiency. Diffused air aeration costs are much more sensitive to air-to-water ratios than is packed tower aeration. Recall, none of these cost estimates included off-gas control. If emission control is a requirement, it is speculated the costs of aeration would likely double.

Figure 9 shows that once an aeration tower is in place the incremental cost of increasing the removal from 90 to 99.99 percent is very low. For a 10 MGD facility, a four log increase in removal for trichloroethylene (from 90% to 99.99%) can be obtained for a 16% increase in cost (from $0.083/1000gal to $0.099/1000gal). Very high levels of removal can be obtained without corresponding increases in cost when packed tower aeration is used.

Development of Cost Equations

The basic engineering design parameters that have the primary impact on the cost of stripping volatile organic chemicals are system size and air-to-water ratio. Therefore an equation was developed as follows for packed-tower aeration based on the configuration shown in Table 9, using standard cost curves (46) and the performance data in Table 8:

$$C_T = K_T Q^a AW^b \qquad (R^2 = 0.98) \qquad (1)$$

where

C_T = unit cost for packed tower aeration in $/1000 gal
K_T = 0.17
a = -0.37
b = 0.06
Q = system design capacity in MGD @ 70% capacity
AW = air-to-water ratio (volume to volume) required to remove a contaminant to a given level

R^2 = goodness of fit (R^2 = 1.00 is a perfect fit)

A similar equation for diffused air aeration was derived as follows:

$$C_B = K_B\ Q^c\ AW^d \qquad (R^2 = 0.92) \qquad (2)$$

where:

C_B = unit cost for diffused air aeration in $/1000 gal

K_B = 0.12
c = -0.23
d = 0.52

The variables Q (system design capcity) and AW (air-to-water ratio) must be given. As shown in an earlier section, air-to-water ratios required for removing a contaminant to a given level are a function of the contaminant and the percentage removal required.

By comparing equations 1 and 2 , it is clear that diffused air aeration is much more sensitive to air to water ratio requirements than is packed tower aeration. Packed tower aeration, therefore, is a technology that could be used in situations where the influent concentrations might be highly variable.

Using equations (1) and (2), cost estimates were made for four operating aeration systems. Table 10 summarizes these estimates and compares them to experienced costs.

As shown by equation 1, the cost of packed tower aeration is heavily influenced by the facility size. The Tacoma facility consists of five individual towers. The estimated unit cost associated with the total facility (5 MGD) is $0.13/1000 gal. A one MGD facility, however, with the same air-to-water ratio (one tower) would have an estimated unit cost of $0.23/1000 gal.

TABLE 10. COMPARISON OF ACTUAL AND ESTIMATED AERATION COSTS

Site	Aerator	Design Capacity (MGD)	Air to Water Ratio (Vol to Vol)	Estimated Cost ($/1000 gal)	Experienced Cost ($/1000 gal)
Tacoma, Washington	Packed Tower	5	300:1	0.13	0.10
Warrington Twp., Pennsylvana	Packed Tower	0.16	40:1	0.10	0.11
Norwalk, Connecticut	Redwood Slat	1.4	28:1	0.18	0.13
Wilmington, Massachusetts	Redwood Slat	1.5	100:1	0.19	0.05

SUMMARY

Aeration is increasingly being used to remove volatile organic compounds from ground water used for drinking. Over three dozen different aeration facilities are in service, but fundamentally, two types exist: those that force air into the water, and those that have the water cascade down through the air. In general, the latter type is less expensive and more commonly used for removing volatile organics.

The theoretical aspects of aeration are well defined, and the ease of stripping a compound from water can be estimated knowing certain molecular properties, particularly the Henry's Law Constant. What remains unknown are verified predictive techniques for the compounds of interest as well as the secondary impacts of aeration (e.g., off-gas emissions). Also, a need exists for a definitive study comparing actual costs and performance. These issues are being resolved by USEPA-DWRD and others. Thus, the topic of aeration and its application for controlling volatile organic compounds in drinking water should be much better understood upon completion of the research now underway.

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APPENDIX A

A DISCUSSION OF UNITS USED TO EXPRESS HENRY'S LAW CONSTANT

In 1802, William Henry, an English physician and researcher, announced the following observation:

> "A given volume of liquid at a specific temperature dissolves a mass of gas proportional to the gas' pressure".

Sometime between 1802 and today, Henry's law evolved to:

> "At equilibrium, the partial pressure of the solute in the gas phase is directly proportional to the solute concentration in the liquid phase". This is mathematically expressed as:

$$Pg \quad Cw \tag{A-1}$$

where:

Pg = partial pressure of the solute in the gas phase, atm

Cw = solute concentration in the liquid phase, $mole/m^3$

then,

$$Pg = HCw$$

or,

$$H = \frac{Pg}{Cw} \tag{A-2}$$

where:

H = Henry's Law Constant, $\frac{atm}{moles/m^3}$ or $\frac{atm\text{-}m^3}{mole}$

When the concentration of the solute is at saturation in both the liquid and vapor phase, the partial pressure, Pg, of the solute is equal to the vapor pressure, Pv, of the pure material, and the concentration of the solute in the liquid phase is equal to its solubility, S.

$$H = \frac{Pv}{S} \tag{A-3}$$

where:

Pv = vapor pressure, atm

S = solubility, moles/m^3

Henry's Law Constant can be expressed in other units, the most common being concentration (weight per volume) in air divided by concentration (weight per volume) in water. The question, therefore, is how does one go from moles/m^3 to mg/L? This can be shown by deriving "H" from vapor pressure and solubility in the Ideal Gas Law:

Calculation of "H" from vapor pressure and solubility at Standard Temperature and Pressure (STP)

$$P_t V = N_t R T_t$$

$$R = \frac{P_t V}{N_t T_t} \qquad \text{(A-4)}$$

where:

T_t = standard temperature = 273°K

P_t = standard pressure = 760 mm Hg

V = unit volume = 1 liter

N_t = total moles of air

R = universal gas constant

$$P_s V = N_s R T_s$$

$$R = \frac{P_s V}{N_s T_s} \qquad \text{(A-5)}$$

where:

T_s = temperature of substance, °K

P_s = vapor pressure of substance, mm Hg

V = unit volume = 1 liter

N_s = moles of substance

R = universal gas constant

Combining equations (A-4 & A-5) yields:

$$\frac{P_t V}{N_t T_t} = \frac{P_s V}{N_s T_s} = \frac{760(1)}{N_t\ (273)} \qquad \text{(A-6)}$$

One mole of any gas occupies 22.4 liters at STP; therefore,

$N_t = \frac{1}{22.4}$ moles, because V = 1 liter.

Solving for $\frac{N_s}{V}$ we get:

$$\frac{N_s}{V} = \frac{P_s\ (273)\ (1)\ \text{moles}}{760\ (T_s)\ (22.4)\ \text{liter}} \quad \text{(concentration in air)} \qquad \text{(A-7)}$$

In order to convert from $\frac{\text{moles}}{\text{liter}}$ to $\frac{\text{mg}}{\text{liter}}$, we must know:

M = gram molecular weight = $\frac{\text{grams}}{\text{mole}}$, and 1 gram = 1000 mg.

$$\frac{\text{mg (in air)}}{\text{liter}} = \frac{P_s(372)}{760(T_s)(22.4)}\ \frac{\text{moles}}{\text{liter}} \times \frac{\text{M grams}}{\text{mole}} \times \frac{1000\ \text{mg}}{\text{gram}} =$$

$$\frac{16.04(P_s)(M)}{T_s}\ \frac{\text{mg}}{\text{liter}} \qquad \text{(A-8)}$$

If the solubility of a substance in water, S, is in mg/L; then,

$$H = \frac{16.04(P_s)(M)}{T_s(S)}\ \frac{\text{mg/L in air}}{\text{mg/L in water}} \qquad \text{(A-9)}$$

where:

P_s = vapor pressure of solute, mm Hg

M = molecular weight, g/mole

T_s = temperature, °K

S = solubility, mg/L

H, calculated as above, is usually reported as dimensionless.

To convert Henry's Law Constant from:

$\frac{\text{atm-m}^3}{\text{mole}}$ to $\frac{\text{mg/L in air}}{\text{mg/L in water}}$:

$$\frac{\frac{(273\ ^\circ\text{K})(\text{M g/mole})(1000\ \text{mg/g})}{(22.4\ \text{L/mole})(T_s, ^\circ\text{K})}\ \text{atm}}{\frac{(\text{M g/mole})(1000\ \text{mg/g})}{1000\ \text{L/m}^3}\ \frac{\text{moles}}{\text{m}^3}} = \frac{\text{mg/L in air}}{\text{mg/L in water}} \qquad \text{(A-10)}$$

$$\frac{273\ (1000)}{(22.4)\ T_x}\ \frac{\text{atm}}{\frac{\text{moles}}{\text{m}^3}} = \frac{\text{mg/L in air}}{\text{mg/L in water}} \qquad \text{(A-11)}$$

$$\frac{273{,}000}{22.4\ T_s}\ \frac{\text{atm m}^3}{\text{mole}} = \frac{\text{mg/L in air}}{\text{mg/L in water}}$$

T_s = 20°C (293°K)

$$\frac{273{,}000}{(22.4)(293)}\ \frac{\text{atm-m}^3}{\text{mole}} = 41.6\ \frac{\text{atm-m}^3}{\text{mole}} = \frac{\text{mg/L in air}}{\text{mg/L in water}} \qquad \text{(A-12)}$$

Sometimes Henry's Law Constant is expressed in "atmospheres" as follows:

$$H = \frac{Pg}{X} \qquad \text{(A-13)}$$

where

H = Henry's Law Constant, atm

Pg = partial pressure of the solute, atm

X = mole fraction of the solute

The mole fraction is defined as the concentration of the contaminant in the solution (K mol/m^3) divided by the sum of the concentrations of all the components in solution (Ref. 4). The molecular weight of water is 18 g/mole and the density of water is 1 g/mL. Therefore, one mole of water

occupies 18 mL, or 0.018 L. Knowing this:

$$\frac{1 \text{ mole}}{0.018 \text{L}} \times \frac{1 \text{ K mole}}{1000 \text{ moles}} \times \frac{1000 \text{ L}}{\text{m}^3} = \frac{55.6 \text{ K mole}}{\text{m}^3} \qquad \text{(A-14)}$$

at saturation:

X, the mole fraction, which is dimensionless, can be calculated:

$$X = \frac{\text{solubility of contaminant, g/L}}{(\text{molecular weight of contaminant, g/mole})\ (55.6 \text{ K } \frac{\text{mole}}{\text{m}^3})} \qquad \text{(A-15)}$$

therefore,

$$H = \frac{\frac{\text{vapor pressure, mm Hg}}{760 \text{ mm Hg/atm}}}{\frac{\text{solubility, g/L}}{(\text{M g/mole})\ (55.6 \text{ K } \frac{\text{mole}}{\text{m}^3})}} = \text{atm} \qquad \text{(A-16)}$$

Similarly, to express H in $\frac{\text{mg/L in air}}{\text{mg/L in water}}$ multiply "atm" x 7.48×10^{-4}

For example, Henry's Law Constant for trichloroethylene may be reported as:

$0.48 \frac{\text{mg/L in air}}{\text{mg/L in water}}$

or,

$11.5 \times 10^{-3} \frac{\text{atm-m}^3}{\text{mole}}$

or,

642 atm

All reported at 20°C (293°K) and 1 atm (760 mm) total pressure

The partition coefficient for trichloroethylene would be:

$$\frac{1}{H} = \frac{1}{0.48} = \frac{2.1 \text{ mg/L in water}}{\text{mg/L in air}}$$

As an additional example, if:

S, contration of solute = 5 moles/m^3

and,

P_g = 0.1 atm (assuming 760 mm total pressure)

then,

$$H = 0.02 \frac{\text{atm-m}^3}{\text{mole}} \quad \text{(at 0°C or 273°K)}$$

or,

$$H = 1112 \text{ atm} \quad \text{(at 0°C or 273°K)}$$

or,

$$H = 0.893 \frac{\text{mg/L in air}}{\text{mg/L in water}} \quad \text{(at 0°C or 273°K)}$$

or,

$$H = 0.832 \frac{\text{mg/L in air}}{\text{mg/L in water}} \quad \text{(at 20°C or 293°K)}$$

APPENDIX B

DEVELOPMENT OF PERFORMANCE PREDICTION EQUATIONS

In order to provide requisite information for use in the cost equations (1) and (2), equations were developed to predict air-to-water ratios for removal of the organic contaminants listed in Table 8.

Equation (B-1) relates the air-to-water ratio to percent removal, and the Henry's coefficient

$$A/W = 29.66\ Rem^{12.44} H^{-0.35} \qquad (R^2 = 0.59) \qquad (B\text{-}1)$$

where

A/W = air to water ratio

Rem = percent removal

H = Henry's coefficient

Equation (B-2) relates air-to-water ratio to percent removal, vapor pressure, solubility and molecular weight.

$$A/W = 3.5 \times 10^6\ Rem^{12.44}\ SL^{-0.35}\ ML^{-1.9}\ V^{-0.75} \qquad (R^2 = 0.72) \qquad (B\text{-}2)$$

where

A/W = air to water ratio

V = vapor pressure

SL = solubility

ML = molecular weight

Equation (B-3) relates air-to-water ratio to percent removal, vapor pressure, solubility and saturation state.

$$A/W = 74.6\ Rem^{12.44}\ SL^{0.37}\ V^{-0.45}\ ML^{-0.18}\ 0.33^{s}\ (R^2 = 0.86) \quad (B\text{-}3)$$

where

A/W = air to water ratio

V = vapor pressure

SL = solubility

ML = Molecular weight

s = Saturation condition. s=0 for saturated compounds and s=1 for unsaturated compounds

Compounds in which all carbon-to-carbon bonding in the molecule are single bonds, as in the methane series of hydrocarbons are called saturated compounds. Compounds in which carbon-to-carbon bonding anywhere within the molecule is represented by double or triple bonds, as in the ethylene and acetylene series of hydrocarbons, are called unsaturated compounds.

APPENDIX C

COST DATA SUMMARY (VOC REMOVAL COSTS)

Contaminant	Capacity* in mgd	ug/L	% Removal	$/1000 gal** Tower	$/1000 gal** Aerated Bssin
Trichloroethylene	.5	100	90	.273	.546
		10	99	.287	.793
		1	99.9	.296	1.032
		.1	99.99	.303	1.270
	1	100	90	.182	.383
		10	99	.191	.611
		1	99.9	.196	.850
		.1	99.99	.202	1.088
	10	100	90	.083	.207
		10	99	.088	.403
		1	99.9	.093	.587
		.1	99.99	.099	.755
Tetrachloroethylene	.5	100	90	.279	.637
		10	99	.293	.935
		1	99.9	.302	1.228
		.1	99.99	.308	1.486
	1	100	90	.186	.460
		10	99	.194	1.752
		1	99.9	.201	1.046
		.1	99.99	.206	1.296
	10	100	90	.085	.277
		10	99	.091	.514
		1	99.9	.098	.726
		.1	99.99	.103	.905
1,1,1-Trichloroethane	.5	100	90	.270	.502
		10	99	.289	.825
		1	99.9	.307	1.421
		.1	99.99	.332	2.572
	1	100	90	.180	.348
		10	99	.192	.644
		1	99.9	.205	1.234
		.1	99.99	.230	2.313
	10	100	90	.082	.176
		10	99	.089	.430
		1	99.9	.102	.860
		.1	99.99	.122	1.821

*To convert from mgd to m^3/day multiply by 3,785
**To convert from $/1000 gal to $/$m^3$ multiply by 0.26412

COST DATA SUMMARY (VOC REMOVAL COSTS)

Contaminant	Capacity* in mgd	ug/L	% Removal	$/1000 gal** Tower	$/1000 gal** Basin
Carbon Tetrachloride	.5	100	90	.264	.428
		10	99	.287	.531
		1	99.9	.272	.600
		.1	99.99	.280	.648
	1	100	90	.176	.292
		10	99	.181	.371
		1	99.9	.184	.427
		.1	99.99	.186	.470
	10	100	90	.081	.133
		10	99	.083	.196
		1	99.9	.084	.247
		.1	99.99	.085	.286
Cis-1,2-Dichloroethylene	.5	100	90	.284	.727
		10	99	.296	1.010
		1	99.9	.304	1.281
		.1	99.99	.310	1.572
	1	100	90	.189	.547
		10	99	.196	.828
		1	99.9	.202	1.098
		.1	99.99	.208	1.379
	10	100	90	.087	.350
		10	99	.093	.571
		1	99.9	.099	.763
		.1	99.99	.104	.966
1,2-Dichloroethane	.5	100	90	.276	.587
		10	99	.285	.749
		1	99.9	.292	.901
		.1	99.99	.297	1.054
	1	100	90	.184	.415
		10	99	.190	.568
		1	99.9	.194	.720
		.1	99.99	.197	.871
	10	100	90	.084	.237
		10	99	.087	.368
		1	99.9	.090	.489
		.1	99.99	.094	.603

*To convert from mgd to m^3/day multiply by 3,785
**To convert from $/1000 gal to $/$m^3$ multiply by 0.26412

COST DATA SUMMARY (VOC REMOVAL COSTS)

Contaminant	Capacity* in mgd	ug/L	% Removal	$/1000 gal** Tower	Basin
1,1-Dichloroethylene	.5	100	90	.262	.406
		10	99	.265	.448
		1	99.9	.270	.500
		.1	99.99	.272	.531
	1	100	90	.174	.274
		10	99	.177	.307
		1	99.9	.180	.348
		.1	99.99	.181	.371
	10	100	90	.080	.121
		10	99	.081	.144
		1	99.9	.082	.176
		.1	99.99	.083	.196